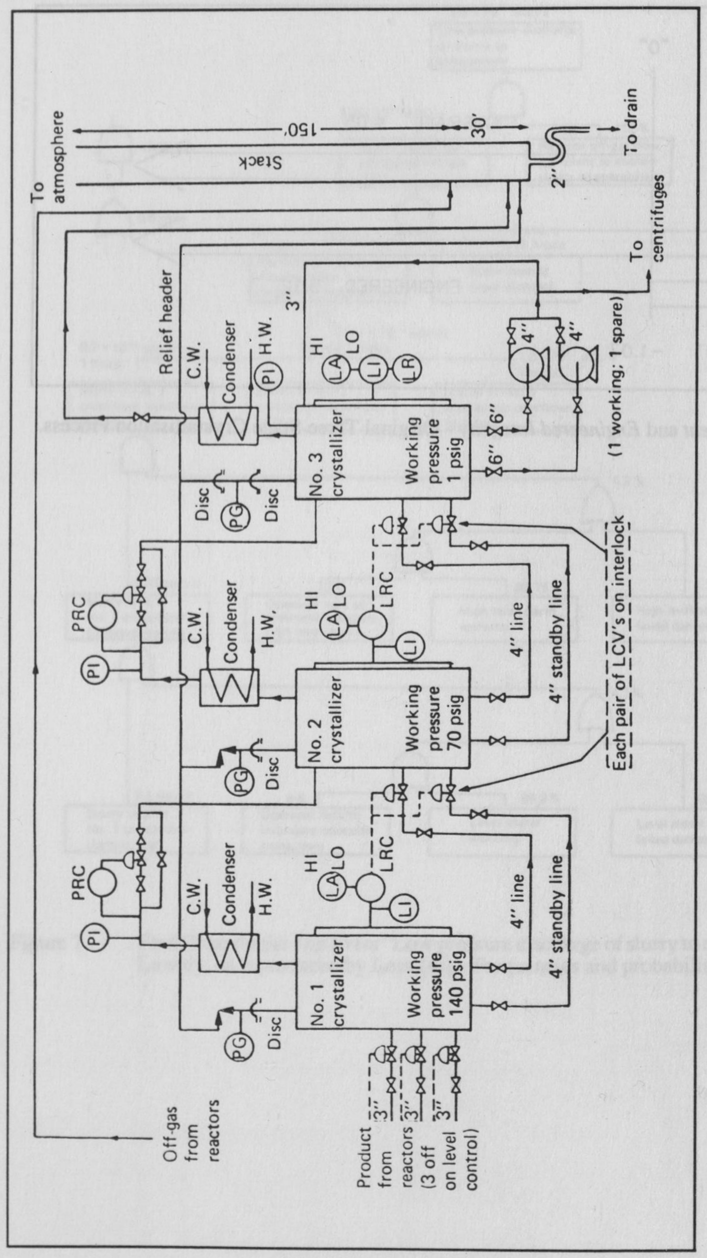

Figure 9 Modified Three Stage Crystallisation Process.

BLOWDOWN OF VESSELS AND PIPELINES

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A computer program has been developed which can be used to simulate the emergency blowdown of vessels and pipelines containing hydrocarbons. The program can predict pressures, temperatures and multi–phase compositions within a vessel or line, temperatures of the wall and rates of efflux, all as functions of time. The program has been validated by comparison with a large number of experimental measurements, most of which were full–scale. Case studies have been conducted to illustrate typical applications of the program.

Keywords: Blowdown, Depressurisation, Pressure Vessels, Pipelines, Safety, Oil & Gas Processing

INTRODUCTION

The rapid depressurisation or blowdown of high pressure vessels and pipelines is a hazardous operation. Such vessels and lines can occur both onshore, for example in a natural gas transmission system, and offshore, on and between platforms. Blowdown can be deliberate, so as to avoid the possiblity of rupture in the event of a fire or to minimise emissions at undesirable locations in the event of a leak, or accidental, if part of a vessel (or its associated pipework or valving) or line is ruptured.

In the case of vessels, blowdown leads to a hazard because of the very low temperatures generated within the fluid in the vessel. This leads to a reduction in the temperature of the vessel walls and possibly to a temperature below the ductile–brittle transition temperature of the steel from which the vessel is fabricated. It can also lead to the formation of hydrates in cases when free water is present in the vessel or to the formation of liquid condensate which can get carried over into a flare or vent system. For blowdown from the top of a slugcatcher of inside diameter 4 m, wall thickness 150 mm and length 50 m containing mainly methane at an initial pressure of 110 bara and temperature of 278 K (5 C) through an orifice of equivalent diameter 50 mm, the minimum gas temperature is about 228 K (–45 C) and the minimum temperature of the inside of the vessel wall in contact with gas is about 243 K (–30 C).

In the case of pipelines, the hazard from blowdown arises not only because of the low temperatures that can arise in the pipe walls but also because of the large total efflux and high efflux rates that arise when the very large inventory in a typical line is blown down. For a 40 km long 0.4191 m (16.5 in) bore gas line containing mainly methane initially at 120 bara and 283 K (10 C), the initial efflux rate following a full–bore rupture is about 3 te/s and a total of about 1000 te can escape if the line is not fitted with sub–sea isolation valves.

Motivated by the need to predict hydrocarbon and vessel and line wall temperatures and also efflux rate, composition and phase, a computer program called BLOWDOWN has been developed by the authors for the simulation of blowdown [1–4]. Because the physical processes occurring during blowdown (fluid mechanics, heat and mass transfer and thermodynamics) are generally extremely complex, development of a complete description – and therefore model – of blowdown is effectively impossible. The main objective of BLOWDOWN is, instead, to simulate all physically significant effects: all insignificant effects are eliminated. Clearly, a great deal of judgement is required in order to be able to select physically significant effects. This judgement is based upon extensive experimental work which has been carried out concurrently with the modelling. The experiments have proved to be invaluable in this sense, as well as providing validation for predictions made using the model. A short description of the main features of BLOWDOWN (more details are given elsewhere [2,4]) and of its experimental validation (more details are again given elsewhere [3,4]) follows, together with two case studies which illustrate typical applications of the program.

BLOWDOWN COMPUTER PROGRAM

The main features of the BLOWDOWN computer program are as follows.

Space discretisation

A vessel is assumed to comprise three distinct zones (see Figure 1):
- a top zone of gaseous hydrocarbon (including evaporated water and suspended liquid droplets which have condensed from the gas);
- a middle zone of liquid hydrocarbon (including dissolved water and gas bubbles which have evaporated from the liquid);
- a bottom zone of free water (including dissolved hydrocarbons).

A pipeline (whether on its own or as part of the blowdown system for a vessel) is divided axially into a number of discrete elements, the size of each of which is varied dynamically during the calculation in such a way that changes in physical properties along the element can be neglected.

Time discretisation

The blowdown is broken down into a sequence of discrete pressure steps. Steps of specified pressure decrement, rather than time steps, are used because pressure is a much more relevant parameter in a thermodynamic sense.

Fluid mechanics

The flow (whether one–phase or two–phase) is assumed to be quasi–steady (that is the mass flow rate is assumed to be the same in every element in a pipeline at a given instant of time) and, for a two–phase flow, to be homogeneous (that is the gas and liquid in an element move at the same velocity). Standard methods are used to determine friction factor and hold–up [5,6].

Thermodynamics

Experimental evidence has shown that it is most important to model the thermodynamics of blowdown accurately since failure to do so can lead to trajectories through phase (pressure–temperature–composition) space which are grossly in error. For this reason, thermodynamic, phase and transport properties of the multi–phase multi–component fluids are calculated rigorously by an extended principle of corresponding states [7,8].

Heat transfer

In a vessel, heat transfer is by:
- forced/natural convection in the top zone;
- nucleate/film boiling in the middle zone;
- natural convection in the bottom zone;
- transient conduction through the wall (including any insulation);
- forced/natural convection to the air or sea surrounding the vessel.

In a pipeline, heat transfer is by:
- forced convection to the fluid (or else heat transfer is ignored and the flow assumed to be either isothermal or adiabatic: experimental evidence is usually consistent with an assumption of isothermal flow as far as blowdown times and rates of efflux are concerned);
- transient conduction through the wall (including any insulation);
- forced/natural convection to the air or sea surrounding the line.

In all cases, standard correlations are used to determine heat transfer coefficients [9–14].

Orifice

Because transit times through the orifice are comparable with times for nucleation and growth of gas bubbles in a volatile liquid, non–equilibrium flashing flow is assumed when just volatile liquid is fed to the orifice. Otherwise, the flow approaching the orifice is assumed to be in thermodynamic and phase equilibrium.

Choking

When choking occurs, whether for a gas, liquid or two–phase (gas–liquid) flow, the mass flow rate is a maximum.

Balance equations

In order to close the system of equations describing blowdown, mass, energy and (for pipelines) momentum balances are performed. The reason why momentum balances are required for pipelines and not vessels is that vessels are assumed to be at a spatially uniform pressure; pipelines are not.

EXPERIMENTAL VALIDATION – VESSELS

Blowdown experiments have mainly been conducted using two different vessels, oriented vertically or horizontally and containing a range of different fluids with blowdown from the top, bottom or side through chokes of various different sizes:
- vessel A (flat ends): length 1.524 m, inside diameter 0.273 m and wall thickness 25 mm;
- vessel B (torispherical ends): tan–to–tan length 2.250 m, inside diameter 1.130 m and wall thickness 59 mm.

Vessel A was oriented either vertically or horizontally, vessel B was always oriented vertically. Transducers were used to measure the pressure, with an estimated accuracy of ±0.2 bar. Bare–wire thermocouples were used to measure the temperature of the fluid within the vessels and also of the inside and outside vessel walls, with an estimated accuracy of ±0.5 K and a response time of order 0.1 s.

The experiments using vessel A were conducted using non–flammable but representative fluids. Nitrogen was used as a representative gas phase since it has critical properties in the same range as those of methane. Carbon dioxide was used as a representative condensible phase such as propane. Fifteen sets of experiments were conducted, covering a range of different fluid compositions, blowdown directions and choke sizes. The initial pressure was about 150 bara and the initial temperature about 290 K (17 C) in all cases. Blowdown times were of order 100 s.

The experiments using vessel B were conducted on mixtures of methane, ethane and propane, together with some on nitrogen. Eighteen sets of experiments were conducted, covering a range of different fluid compositions, blowdown directions and choke sizes. The initial pressure was about 120 bara in all but two cases and the initial temperature between 290 K (17 C) and 305 K (32 C). Blowdown times were of order 1500 s.

Predictions made using the BLOWDOWN program have been compared with all of the validatory experiments. One point that must be borne in mind when comparing the experimental results and the BLOWDOWN predictions is that the program contains no disposable parameters. There has, therefore, been no adjustment of parameters in order to ensure good agreement between the experimental measurements and the predictions. In order to give some feel for the agreement between the experimental results and the BLOWDOWN predictions, two representative examples will be examined.

In the first example, vessel A was oriented vertically and nitrogen blown down from the top through a choke of equivalent diameter 6.35 mm. The experimental results are summarised in Figure 2, which gives the variation with time of the pressure in the vessel, and Figure 3, which gives the variations with time of the bulk gas and inside wall temperatures. Also shown on the figures are predicted variations made using BLOWDOWN. There is clearly excellent agreement between the measured and predicted pressures in the vessel. This illustrates the more general result that it is relatively easy to predict the pressure decay rate using any physically reasonable assumptions. Clearly, there is also good agreement between the measured and predicted bulk gas and inside wall temperatures. Interpolation and smoothing of the spatial variations in the gas temperature give the isotherms shown on the left–hand side of Figure 4. These indicate the presence and hence importance of natural convection within the vessel, schematic streamlines for which are shown on the right–hand side of Figure 4.

In the second example, vessel B was oriented vertically and 66.5 mole% methane, 3.5 mole% ethane and 30.0 mole% propane blown down from the top through a choke of equivalent diameter 10 mm. The experimental results are summarised in Figure 5, which gives the variation with time of the pressure in the vessel, Figure 6, which gives the variations with time of the bulk gas and bulk liquid temperatures, and Figure 7, which gives the variations with time of the temperatures of the inside of the wall in contact with the gas and with the liquid. Also shown on the figures are the predicted variations made using BLOWDOWN. There is again excellent agreement between the measured and predicted pressures in the vessel. There is also reasonable, and usually good, agreement between the measured and predicted bulk gas, bulk liquid and inside wall temperatures.

It follows from the comparisons reported here and from others reported elsewhere [3] that the BLOWDOWN program predicts results which are in close agreement with experimental measurements: minimum average bulk fluid and wall temperatures can be predicted with an estimated typical uncertainty of ±3 K. This agreement permits confidence to be placed in the predictions made using BLOWDOWN.

EXPERIMENTAL VALIDATION – PIPELINES

There has been relatively little practical investigation of very rapid blowdown of large lines containing hydrocarbons. There were, of course, the accidental blowdowns following the sequential, probably full–bore, rupture of the three gas lines connected to Piper Alpha, one of which, that between Piper and MCP–01, was monitored sufficiently well to give useful validatory information. The blowdown of this line is discussed in the second case study.

As far as lines containing condensate (that is volatile liquid hydrocarbon) are concerned, there appears to have been no properly documented rapid blowdown of a full–size line. Probably the most useful and thorough experiments have been conducted on a line of length 100 m and bore 0.15 m (nominally 6 in) containing LPG (commercial propane) at initial pressures of up to 21 bara and initial temperatures of about 293 K (20 C) through orifices ranging in equivalent diameter from 10 mm to 150 mm (full–bore) [15]. Although the precise composition of the LPG is not given, it turns out that it does not matter too much. Accordingly, the LPG has been assumed to comprise 95 mole% propane and 5 mole% butane for modelling purposes. The initial pressure in the line was 11 bara and the initial temperature was 293 K (20 C). The assumed roughness length–scale was 0.05 mm.

The measured and predicted variations with time of the pressure and temperature at the intact end of the line and of the inventory of the line are given in Figures 8, 9 and 10, respectively. There is clearly good agreement between the values measured experimentally and those predicted using BLOWDOWN. Alteration of the assumed composition to 90 mole% propane and 10 mole% butane changes the predicted pressure and temperature at the intact end of the line by less than 0.5 bar and 1 K, respectively, and the inventory of the line by less than 1%. The only experimental feature not predicted by BLOWDOWN is the small pressure undershoot near the start of the blowdown (see Figure 8). This undershoot is determined by the usually irrelevant dynamics of the initial expansion wave.

CASE STUDY: BLOWDOWN OF GAS–CONDENSATE SEPARATOR

The first case study concerns blowdown of a high pressure gas–condensate separator. The carbon steel vessel is taken to be vertical and of tan–to–tan length 10 m, inside diameter 4 m, wall thickness 120 mm and to have hemispherical ends of thickness 80 mm. The choke is of 50 mm equivalent diameter and blowdown to atmosphere is either from the top or from the bottom. The hydrocarbon feed to the vessel is of the following composition: methane: 75 mole%, ethane: 5 mole%, propane: 3 mole%, butane: 4 mole%, pentane: 4 mole%, hexane: 4 mole%, heptane: 3 mole%, octane: 2 mole%. Liquid hydrocarbon condensate initially fills 20 vol% and the co–existing gas phase 80 vol% of the vessel. The initial pressure is 100 bara and the initial temperature 283 K (10 C). The vessel is assumed to be standing in freely–convecting air at a temperature of 278 K (5 C).

The predicted variations with time of the pressure in and inventory of the vessel are shown in Figures 11 and 12, respectively. In both figures, lines marked T refer to blowdown from the top and lines marked B to blowdown from the bottom. The main features of the blowdowns are as follows:

- blowdown to essentially atmospheric pressure takes about 3000 s, irrespective of whether blowdown is from the top or bottom of the vessel;
- the initial fluid inventory in the vessel is 31.6 te: when the vessel has been blown down, the remaining inventory in the vessel is about 16.3 te when blowdown is from the top of the vessel and about 0.1 te when it is from the bottom;
- the maximum efflux rate through the choke is about 0.027 te/s (110 MMSCFD)

when blowdown is from the top of the vessel and about 0.154 te/s (420 MMSCFD) when it is from the bottom;
• the minimum bulk gas temperature is about 222 K (–51 C) when blowdown is from the top of the vessel and about 220 K (–53 C) when it is from the bottom;
• the minimum inside wall temperature is about 267 K (–6 C) when blowdown is from the top of the vessel and about 261 K (–12 C) when it is from the bottom.

The principal distinction between blowdown from the top of the vessel and blowdown from the bottom is the rate of decrease of inventory in the vessel. Although vessels are usually blown down from the top at present, there is an increasing interest (especially after events on Piper Alpha) in blowdown of vessels containing significant quantities of flammable liquid from the bottom since doing so minimises the inventory which might otherwise feed a fire [16]. Of course, blowdown from the bottom also leads to a flow mainly of liquid out of the vessel which could not normally be fed directly to a flare or vent. (In this case study, however, it turns out that the liquid condensate is sufficiently volatile that it flashes to form mainly gas downstream of the choke which could be fed directly to a flare or vent. The problem would then be the very high flow rate which would probably necessitate use of a choke with a smaller equivalent diameter, at least during the early part of the blowdown.) There are, therefore, problems associated with the disposal of significant quantities of liquid: storage in another vessel such as a flare knock–out drum can just alter the location of the hazard.

CASE STUDY: BLOWDOWN OF GAS LINE

The second case study concerns the probable [16] full–bore blowdown of the gas line between the Piper Alpha and MCP–01 platforms on the evening of 6th/7th July 1988. It is based on evidence [17] given by the authors to the Public Inquiry into the tragedy on Piper. The line was of the following dimensions:
• sub–sea line length: 53804 m;
• sub–sea line bore: 0.4191 m;
• riser height (from sea bed to topsides): 160 m;
• riser bore: 0.4064 m;
• roughness length–scale (assumed): 0.063 mm;
• orifice diameter (assumed full–bore at top of riser on Piper): 0.4191 m.
The gas in the line had the following composition: methane: 73.60 mole%, ethane: 13.40 mole%, propane: 7.40 mole%, butane: 1.40 mole%, pentane: 0.15 mole%, hexane: 0.02 mole%, nitrogen: 4.03 mole%. The initial pressure in the line was 117 bara and the initial temperature was 283 K (10 C), assuming that the gas adopted a typical summer–time sea temperature. Hence the initial inventory in the line was 1280 te (51 MMSCF).

The measured and predicted variations with time of the pressure at the intact (MCP–01) end of the line are given in Figure 13. There is clearly good agreement between the values logged at MCP–01 and those predicted using BLOWDOWN.

It is of interest to investigate the effect on the total efflux from the line of fitting an SSIV (sub–sea isolation valve). In addition to the base case:
• case 1: no SSIV in the line;
already discussed and corresponding to the actual case at Piper, two cases have been investigated:
• case 2: an SSIV at a distance of 400 m along the sea–bed from the base of the riser at Piper;
• case 3: an SSIV at a distance of 200 m along the sea–bed from the base of the riser at Piper.
The SSIV is assumed to start to close 60 s after rupture of the line, since it would

take about this length of time for the rupture to be detected and for valve closure to be initiated. It is assumed that there is a linear reduction of flow area with time while closing the SSIV and that closure takes 20 s, which is based on the rule–of–thumb that 1 in of closure takes about 1 s.

The predicted variation with time of the total mass efflux from the line is given in Figure 14: line 1 refers to case 1, line 2 to case 2 and line 3 to case 3. The main features of the blowdown are as follows:
• in all three cases, immediately after rupture of the line, the flow is choked and the mass flow rate out of the line is about 3 te/s;
• in case 1 (no SSIV), about 1270 te (that is virtually all of the gas) has left the line when blowdown effectively ceases about 25000 s (7 hr) after rupture of the line;
• in case 2 (SSIV located 400 m from riser), about 37 te has left the line when blowdown effectively ceases about 90 s after rupture of the line;
• in case 3 (SSIV located 200 m from riser), about 36 te has left the line when blowdown effectively ceases about 90 s after rupture of the line.
Clearly, fitting an SSIV, whether 400 m (case 2) or 200 m (case 3) from the riser drastically reduces the amount of gas leaving the line and hence the threat to the platform compared with fitting no SSIV (case 1). Moreover, fitting an SSIV close to the platform (200 m from the riser; case 3), with possible risk of damage to the SSIV from debris falling from the platform and from the anchors of ships, does not give a large reduction in the amount of gas leaving the line compared with fitting it some distance away (400 m from the riser; case 2).

CONCLUSION

The BLOWDOWN program described here is based on very accurate thermodynamics since experimental evidence has shown that to do so is essential. Given such thermodynamics and associated thermophysical properties, extensive use is then made of appropriate established correlations for heat transfer and fluid mechanics. The accuracy of the predictions made using BLOWDOWN stems from the accuracy of the thermodynamics and the appropriateness of the correlations. Relaxation of either can and does lead to significant errors. It should be recalled that BLOWDOWN is a completely predictive model in the sense that it contains no disposable parameters which can be adjusted to fit particular circumstances. Confidence in its predictions comes from its validation by comparison with experimental measurements.

Further developments of BLOWDOWN to extend its applicability include:
• blowdown of multiple vessels/pipelines through multiple chokes;
• blowdown of a vessel containing internals with significant thermal mass;
• blowdown of a vessel or pipeline on which there is an external fire loading;
• validation for higher molecular weight hydrocarbons;
• validation for systems containing free water;
• validation for flashing liquid flows through orifices;
• relaxation of the assumption of homogeneous quasi–steady flow in pipelines.
Work is in hand on each of these.

BLOWDOWN has now been used by many oil and gas companies for the simulation of future and existing depressurisation systems. Applications have included a large number of individual vessels on offshore platforms and onshore installations, a number of multiple vessels connected to common blowdown headers, sub–sea pipelines and also accident investigation. BLOWDOWN can, therefore, be used confidently as an engineering tool for the design of depressurisation systems.

ACKNOWLEDGEMENT

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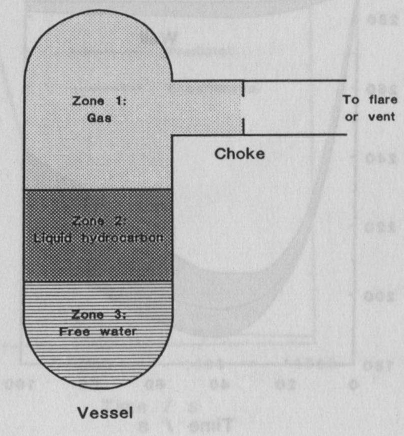

Figure 1 Schematic diagram of vessel with blowdown from top

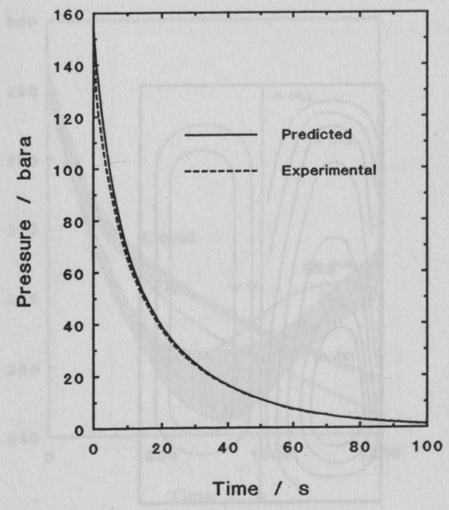

Figure 2 Pressure in vessel A

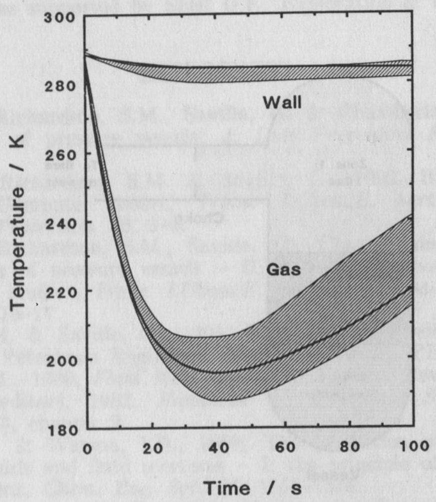

Figure 3 Bulk gas and inside wall temperatures in vessel A: hatched regions span experimental measurements, solid lines are predictions

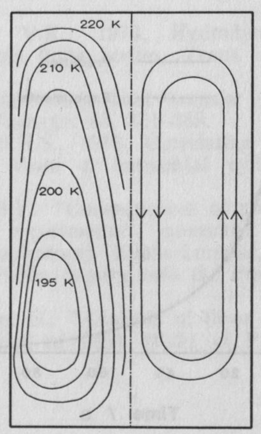

Figure 4 Isotherms (left–hand side) and schematic streamlines (right–hand side) in vessel A: horizontal scale is exaggerated for clarity

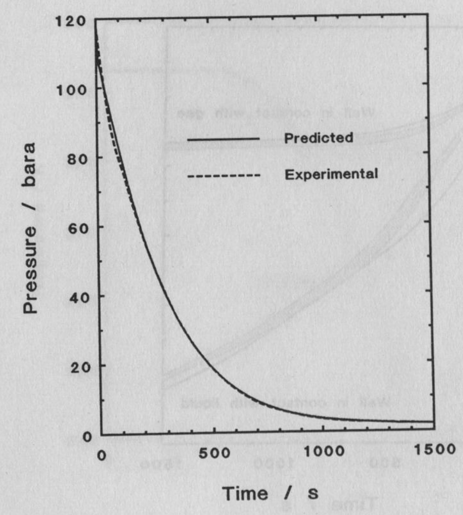

Figure 5 Pressure in vessel B

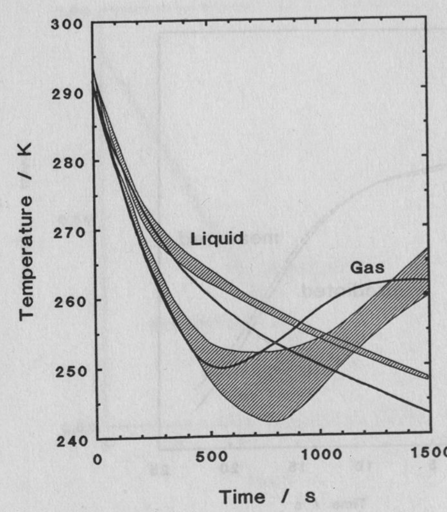

Figure 6 Bulk gas and bulk liquid temperatures in vessel B: hatched regions span experimental measurements, solid lines are predictions

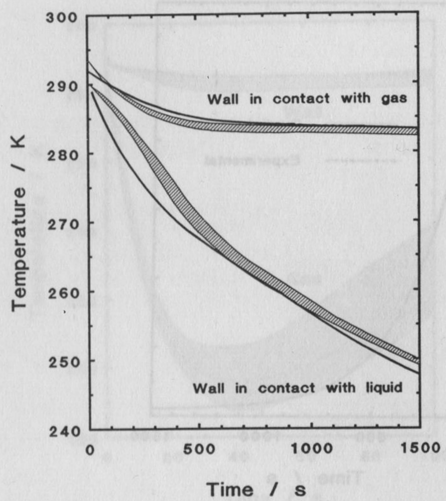

Figure 7 Inside wall temperatures in vessel B: hatched regions span experimental measurements, solid lines are predictions

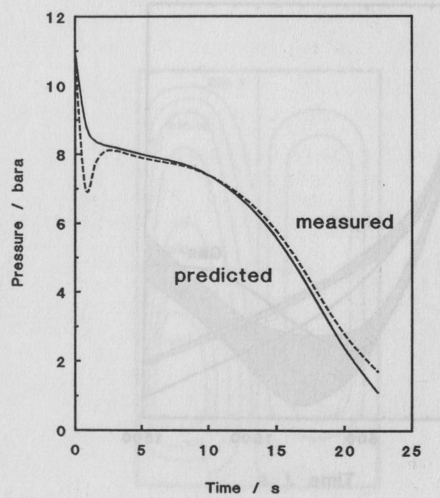

Figure 8 Pressure at intact end of LPG line

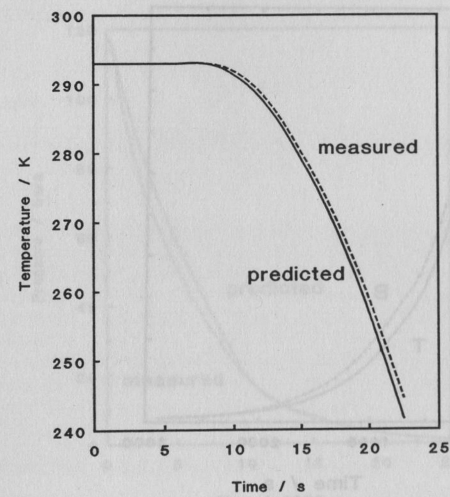

Figure 9 Temperature at intact end of LPG line

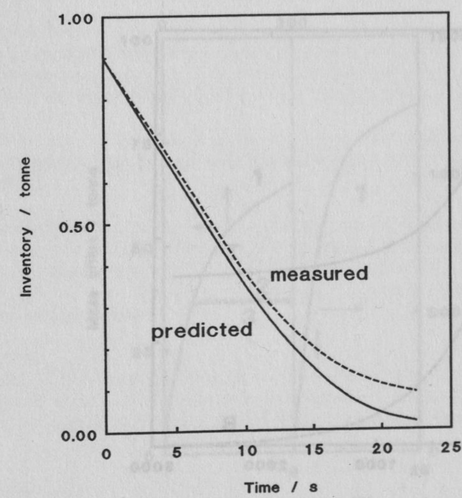

Figure 10 Inventory of LPG line

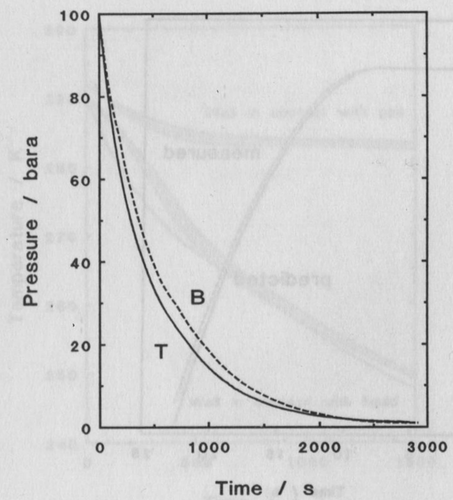

Figure 11 Pressure in gas–condensate separator: T refers to blowdown from top and B to blowdown from bottom

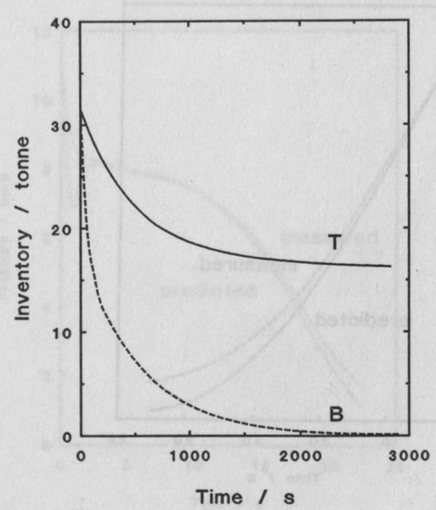

Figure 12 Inventory of gas–condensate separator: T refers to blowdown from top and B to blowdown from bottom

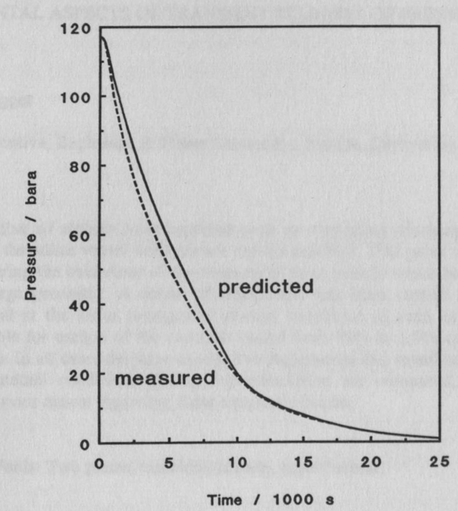

Figure 13 Pressure at intact (MCP–01) end of line

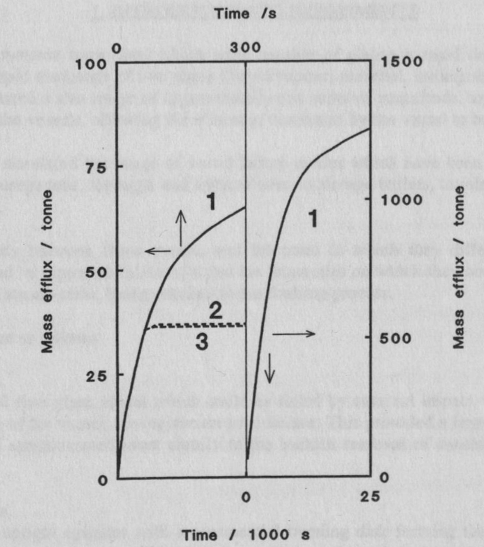

Figure 14 Total mass efflux out of ruptured (Piper) end of line: line 1 refers to case 1, line 2 to case 2 and line 3 to case 3